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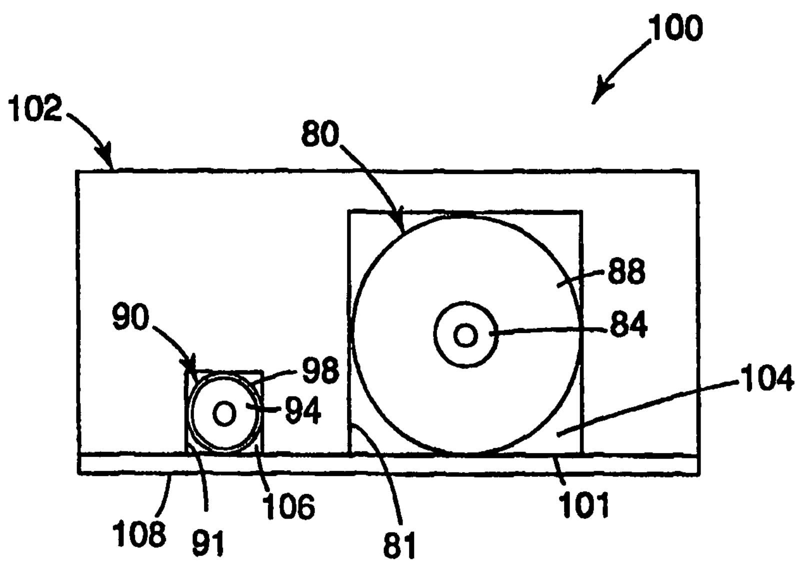
With amended claims.

(54) Title: SENSING TAPES FOR STRAIN AND/OR TEMPERATURE SENSING

(57) Abstract

A tape to be mounted on a workpiece includes an elongated support ribbon and an optical fiber attached to the support ribbon.



SENSING TAPES FOR STRAIN AND/OR TEMPERATURE SENSING

Background of the Invention

The invention relates generally to optical waveguides and more specifically to optical fibers.

Optical fibers are used to guide light which might, typically, be an optical signal used in telecommunications or in sensing applications. Some optical fibers can be described as a thin strand of light-transmitting medium. In general, an optical fiber includes an inner core and an outer cladding having an effective index of refraction less than the inner core. Some optical fibers, however, have a complex structure made from an inner core surrounded by several outer cores, or claddings, each having different effective indices of refraction. The difference in the effective index of refraction creates internal reflections forcing the light to propagate along the inner core and preventing it from leaking out of the fiber.

Some optical fibers include Bragg gratings (BG). A Bragg grating is formed by producing a series of perturbations in the index of refraction of the inner core. Typically, the perturbations are formed by exposing the core through the cladding to an interference pattern of two ultraviolet beams directed against the optical fiber. The spacing of the perturbations creates a grating characterized by a center wavelength at which light will no longer propagate through the optical fiber. Bragg gratings with different perturbation spacings have different center wavelengths. In general, Bragg gratings are

classified either as short period gratings or as long-period gratings. Long-period gratings are those in which the spacing of the perturbations is at least 10 times larger than the wavelength of input light. Typically, the period is in the range 15-1500 μm for center wavelengths between 700 and 1500 nm. In addition, long-period gratings can have a span of perturbations extending for a few cm. On the other hand, short period gratings have a span of a few 100 microns to several cm and a period in the range 0.2 - 0.7 μm for center wavelengths between 600 and 2100 nm.

Bragg gratings are used in optical fibers to filter out selected wavelengths from an optical signal, e.g., like a notch filter. As an optical signal propagates through the core and encounters a short period grating, specific wavelengths of light, which corresponds to the resonant or center wavelength of the grating, are reflected back along the inner core. When an optical signal encounters a long-period grating, the center wavelength of the grating is converted from a guided mode of the core to a non-guided mode of the cladding. A guided mode propagates through the core of the optical fiber. A non-guided mode of the cladding dissipates through the cladding and does not propagate through the optical fiber. The center wavelength reflection or conversion from a guided mode to a non-guided mode is a function of the perturbation spacing of the Bragg grating. The center wavelength of the Bragg grating is sensitive to strain and temperature. Strain and/or change in temperature causes the center wavelength to shift. Typically, for a long-period grating a central wavelength of 1550 nm shifts by about 1 to 1.5 nm per 100°C change in temperature and by about 0.12 nm per 100 microstrain change in strain.

Summary of the Invention

In general, in one aspect, the invention features a tape to be mounted on a workpiece. The tape includes an elongated ribbon and an optical waveguide (e.g. optical fiber) supported by the elongated ribbon.

The optical fiber can be attached along the elongated direction of the elongated ribbon. The optical fiber can include a Bragg grating and an outer coating. The outer coating can have a thickness and flexibility chosen to isolate substantially the optical fiber from the workpiece. The outer coating also can have a thickness and flexibility chosen to allow effective transfer of strain from the workpiece to the optical fiber. The outer coating can be a polyamide. The optical fiber also can include a plurality of Bragg gratings.

In another aspect, the invention features a tape to be mounted on a workpiece. The tape includes an elongated ribbon, a first optical fiber supported by the elongated ribbon, and a second optical fiber supported by the elongated ribbon.

The first and second optical fibers can be attached along the elongated direction of the elongated ribbon. The first and second optical fibers can include a Bragg grating. The first optical fiber also can include a first coating. The first coating can have a thickness and flexibility chosen to isolate substantially the first optical fiber from the workpiece. The second optical fiber also can include a second coating. The second coating can have a thickness and flexibility chosen to allow transfer of strain from the workpiece to the second optical fiber.

In another aspect, the invention features a method of producing a tape. The method includes providing a coated optical fiber and supporting the optical fiber with an elongated ribbon.

The step of supporting the optical fiber can include a step of attaching the optical fiber along the elongated direction of the elongated ribbon. The step of providing a coated optical fiber can include a step of coating an optical fiber with coating.

The invention provides a sensing tape by embedding a coated optical fiber into a support ribbon. The sensing tape is easily attached to a support structure to monitor strain and/or temperature. Also, the tape can be easily packaged by simply winding the tape onto a spool from which the desired amount of tape can be unwound at the time of installation and/or use.

Brief Description of the Drawing

Fig. 1 illustrates a sensing tape for measuring strain and temperature;

Fig. 2 illustrates a sensing tape for measuring temperature;

Fig. 3 illustrates a sensing tape for measuring strain; and

Fig. 4 shows a sensing tape wound on a support form.

Description of the Preferred Embodiments

The sensing tapes discussed herein are used to monitor or detect changes in strain and/or temperature. In general, sensing tapes include an optical fiber embedded in or mounted on a flexible elongated support ribbon.

Referring to Fig. 1, sensing tape 40 which senses both strain and temperature includes an optical fiber 50 held into a longitudinal groove 61 of a support ribbon 60 by an epoxy 64, e.g., TRA Bond-F118 epoxy from TRA-CON, located in Bedford, Massachusetts. Optical fiber 50 includes an outer cladding 54 and an inner core 52 having a Brag grating (not shown). Outer cladding 54 is coated with a coating 58 designed to allow effective strain transfer from the support ribbon 60 to the optical fiber 50. The effective transfer of strain is a function of the thickness and flexibility of the coating. The flexibility of the coating is characterized by an elasticity modulus. A typical sensing tape used for sensing both strain and temperature includes an optical fiber having a thin coating of an inelastic polymer, e.g., 25 micron polyamide coated fiber, a 115 micron thick cladding of glass, e.g., SiO_2, and a 10 micron thick core of glass, e.g., SiO_2. The core also can be doped with other materials, e.g., germanium. The coating material can be made from similar materials, e.g., polymers, having a suitable thickness and flexibility. As a general rule, a thicker coating of a material attenuates the amount of strain transferred more than a thinner coating of the same material. In practice, the coating material is designed to be thin and inelastic such that the effects of strain transferred through the epoxy 64 to optical fiber 50 are not substantially attenuated. For example, the coating is selected such that the transfer of strain is attenuated by less than 5%. A bonding layer 66 covers a groove side 63 of support ribbon 60 and is used to attach sensing tape 40 to the structure being monitored, e.g., a support beam of a bridge or an airplane wing.

Once mounted to a structure, changes in strain and temperature are transferred from the structure to optical fiber 50, i.e., through bonding epoxy 64 to optical fiber 50. Strain and temperature changes transferred to the optical fiber cause the center wavelength of the Bragg grating to shift. The shift of the center wavelength of a Bragg grating is a function of both strain and change in temperature. Therefore, both strain and change in temperature transferred from the support structure to the optical fiber can be sensed by monitoring the shift of the center wavelength.

The response of the center wavelength is expressed by Eq. 1

$$\Delta\lambda = \lambda(\eta\varepsilon + \xi\Delta T) \qquad (1)$$

where $\Delta\lambda$ is the wavelength change caused by strain (ε) and change in temperature (ΔT). λ is the center wavelength of the grating at room temperature and zero applied strain. η is the strain-optic coefficient and ξ is the temperature coefficient. The value of the strain-optic coefficient and the value of the temperature coefficient depend upon the geometry and materials used in optical fiber fabrication. Each optical fiber possess an unique set of strain-optic and temperature coefficients. For a single mode fiber made from SiO_2, η is typically about 0.75-0.80 microstrain^{-1}. ξ is typically about 6-8 x 10^{-6} °C^{-1}.

If sensing tape 40 is placed in a constant temperature environment, then the change in center wavelength can be attributed to strain alone. That is, since $\lambda T = 0$, the second term in the right hand side of

Eq. 1, $\lambda\xi\Delta T$, is also zero and Eq. 1 can be rewritten as:

$$\Delta\lambda = \lambda\eta\varepsilon \qquad (2)$$

Conversely, if sensing tape 40 is placed in an environment in which it is known that there is no strain, then the change in center wavelength can be attributed to ΔT alone. That is, since $\varepsilon = 0$, the first term in the right-hand side of Eq. 1, $\lambda\eta\varepsilon$, is also zero and Eq. 1 can be rewritten as:

$$\Delta\lambda = \lambda\xi\Delta T \qquad (3)$$

In some sensing applications, where both strain and temperature changes are present, it may be desirable to sense only change in temperature. Referring to Fig. 2, a sensing tape 10, which senses only change in temperature, includes an optical fiber 20 held in a longitudinal groove 31 of a support ribbon 32 by epoxy 34, e.g., a soft silicon rubber based epoxy, such as Dow Corning's gasket sealant which has very low stiffness. As before, optical fiber 20 includes an outer cladding 24 and an inner core 21 having a Bragg grating (not shown). Outer cladding 24 is coated with a coating 28 designed to substantially isolate optical fiber 20 from strains experienced by the structure to which support ribbon 32 is attached. The amount of isolation, and thus the attenuation in strain transfer to the optical fiber, is dictated by the thickness and flexibility of coating 28. The thicker and more flexible the coating, the more effective the isolation will be. Thus, it can be

observed in a fiber will be due to changes in temperature and not due to strain associated with the structure being monitored.

A typical sensing tape used for sensing change in temperature uses a thick coating of an elastic polymer, e.g:, a 600 micron acrylate coating. As described above, the coating can be made from a wide range of materials. In general, it is desirable to select the thickness and elasticity of the coating so as to attenuate substantially the strain transferred through the epoxy 34 to optical fiber 20 so that the observed changes in the center wavelength are due to changes in temperature of the structure being monitored. For example, the thickness and elasticity of the coating are selected so as to attenuate the strain transfer by a factor of at least 10. In practice, the factor necessary to attenuate the strain transfer is related to the magnitude of the change in strain on the structure being monitored. For example, in sensing applications where large changes in strain are present, the thickness and elasticity of the coating are selected so as to attenuate the strain transfer by a factor that is greater than 10.

Referring to Fig. 2, a sealing layer 38 hermetically seals a groove side 33 of support ribbon 30 and prohibits foreign species, e.g., air, biological species, and chemical species, from interacting with coating 28. A bonding layer 36 covers sealing layer 38 and is used to attach the temperature sensing tape 10 to a support structure 1.

By properly selecting the thickness and flexibility of the epoxy, the bonding layer, and the support ribbon also one can further isolate the fiber from stain.

support ribbon also one can further isolate the fiber from stain.

As seen in Eq. 1, if the strain transfer is significantly attenuated so that $\lambda\eta\varepsilon$ is approximately zero, then the observed changes in the center wavelength will be attributable to changes primarily in temperature as shown in Eq. 3.

In other sensing applications, where both strain and temperature changes are present, it may be desirable to sense only strain. Referring to Fig. 3, sensing tape 100 which can be used to sense changes in strain includes two optical fibers 80, 90. Optical fiber 90 is similar to the optical fiber as shown in Fig. 1 and includes a coating 98 and a cladding 94. Optical fiber 80 is similar to the optical fiber as shown in Fig. 2 and includes a coating 88 and a cladding 84. Optical fiber 80 is held in a first longitudinal groove 81 of support ribbon 102 by an epoxy 104. Optical fiber 90 is held in a second longitudinal groove 91 of support ribbon 102 by an epoxy 106. A bonding layer 108 covers a groove side 101 of support ribbon 102.

As described above, the thick and elastic coating on optical fiber 80 minimizes the amount of strain, $\lambda(\eta\varepsilon)$, transferred to optical fiber 80 such that the center wavelength shift of the Bragg grating responds primarily to temperature, $\Delta\lambda = \lambda\xi\Delta T)$. The thin and inelastic coating on optical fiber 90 allows strain transfer such that the center wavelength of the Bragg grating responds to the combined amount of strain and temperature, $\lambda(\eta\varepsilon + \xi\Delta T)$. The center wavelength shift of optical fiber 80 is a measure of the change in temperature, $\Delta\lambda_{80} = \lambda\xi\Delta T$, and the center wavelength

shift of optical fiber 90 is a measure of both strain and change in temperature, $\Delta\lambda_{90} = \lambda(\eta\varepsilon + \xi\Delta T)$. The difference of the monitored change in center wavelengths is a direct measure of strain alone, as can be seen from the following:

$$\Delta\lambda_{90} - \Delta\lambda_{80} = \lambda\eta\varepsilon \qquad (4)$$

The sensing tapes described above can be used in a variety of sensing applications. For example, a temperature sensing tape can be used in an environment with constant temperature, e.g., probes used to detect oil and water wells, to monitor or detect acoustic signals. In addition, a sensing tape having a reactive coating can be used to detect the presence of chemical or biological species. For example, a chemical species can react with the coating to cause a change in the flexibility of the coating. The change in the flexibility of the coating affects the amount of strain transferred to the optical fiber which, in turn, affects the sensitivity of the center wavelength shift to changes in strain.

The optical fibers used in sensing tapes can include single mode optical fibers, in-line etalon optical fibers, intrinsic fabry-perot optical fibers, or any optical fiber having optical characteristics, e.g., a center wavelength shift or phase shift, affected by changes in strain and/or temperature. In addition, the optical fibers also can include several Bragg gratings each Bragg grating having the same or different a center wavelengths. In general, each Bragg grating is spaced apart by 2 inches to several hundred meters. Typically, span of each grating can be from 0.5mm to several meters.

The optical fibers can be attached along the length of the support ribbon using any technique known to those skilled in the art. For example, an optical fiber can be embedded between two support ribbons. Alternatively, the optical fiber and support ribbon can be co-extruded simultaneously to produce an optical fiber embedded in a ribbon. In addition, the optical fiber can be attached to the top of a support ribbon. The support ribbon also can be wound into a helix, e.g., like a spring. An optical fiber can be attached along the elongated direction of the support-ribbon before or after the support ribbon has been wound into a helix. Alternatively, an optical fiber can be supported by the support ribbon by winding the ribbon into a helix around the optical fiber. In this case, strain is not transferred from the support ribbon to the optical fiber, because the optical fiber is not attached to the support ribbon. The support ribbon can be any shape, such as, flat or round. For example, the support ribbon can be a round teflon tube. The optical fiber can be inserted into and attached within a central bore of the teflon tube. Alternatively, the teflon tube can be formed around the optical fiber. optionally, an optical fiber is supported by a teflon tube by inserting the optical fiber into a central bore of the tube. In this case, strain is not transferred from the teflon tube to the optical fiber because the optical fiber is not attached to the teflon tube. The support ribbon also can include a marking which indicates where the.Bragg gratings are located. Once attached or embedded into the support ribbon, the sensing tape can be stored in a roll. During installation, the support ribbon can be unrolled and cut to a desired length.

The support ribbon also can include additional adhesives used to attach the ribbon to the support structure, e.g., a graphite composite epoxy which cures under applied pressure and heat. In addition, the support ribbon can include a paper backing applied to the bonding layer. During installation, the paper backing is removed and the sensing tape is attached to the support structure via the bonding layer.

Referring to Fig. 4, a convenient way of packaging and/or storing the sensing tape 300 is to wind it around a core 302 (e.g., a cylindrically shaped member) to form a compact reel of tape (e.g., like adhesive tape commonly found in office supply outlets). When sensing tape is needed for a particular application it is simply unwound from the reel or core and used. The remainder of unused tape remains conveniently wound on the core.

Other embodiments are within the following claims. For example, though we have described sensing tapes which incorporate optical fibers into or onto a ribbon structure, the invention covers the use of any optical waveguide on a ribbon structure including, for example, plastic fibers. Also, the tapes that are constructed in accordance with the invention can be used for purposes other than sensing. That is, the invention is meant to cover optical waveguides into a ribbon structure or any purpose including simply improving ease of applying or attaching such waveguides to workpieces. Also, the tape can be formed to have an adhesive surface or the adhesive can be supplied at the time of applying the tape to the workpiece.

Claims:

1. A tape to be mounted on a workpiece, said tape comprising:

an elongated flexible ribbon; and

an optical waveguide supported by the elongated ribbon along the elongated direction of the ribbon.

2. The tape of claim 1, wherein the optical waveguide is an optical fiber.

3. The tape of claim 2, wherein the optical fiber includes a Bragg grating.

4. The tape of claim 2, wherein the optical fiber includes an outer coating.

5. The tape of claim 4, wherein the outer coating is a polyamide.

6. The tape of claim 4, wherein the outer coating has a thickness and flexibility chosen to isolate substantially the optical fiber from the workpiece.

7. The tape of claim 4, wherein the outer coating has a thickness and flexibility chosen to allow effective transfer of strain from the workpiece to the optical fiber.

8. The tape of claim 2, wherein the optical fiber includes a plurality of Bragg gratings.

9. The tape of claim 2 wherein said ribbon has a top surface and a bottom surface, said tape further comprising an adhesive on said bottom surface.

10. The tape of claim 2 further comprising a core around which the ribbon and optical fiber are wound.

11. A tape to be mounted on a workpiece, said tape comprising:

an elongated flexible ribbon;

a first optical waveguide supported by and affixed to the elongated ribbon along the elongated direction of the ribbon; and

a second optical waveguide supported by and affixed to the elongated ribbon along the elongated direction of the ribbon.

12. The tape of claim 11, wherein the first optical waveguide is a first optical fiber and the second optical waveguide is a second optical fiber.

13. The tape of claim 12, wherein the first optical fiber includes a Bragg grating.

14. The tape of claim 13, wherein the second optical fiber includes a Bragg grating.

15. The tape of claim 12, wherein the first optical fiber include a first coating and the second optical fiber includes a second coating.

16. The tape of claim 15, wherein the first coating has a thickness and flexibility chosen to substantially isolate the first optical fiber from strain in the workpiece.

17 The tape of claim 15, wherein the second coating has a thickness and flexibility chosen to allow effective transfer of strain from the workpiece to the second optical fiber.

18. The tape of claim 12 wherein said ribbon has a top surface and a bottom surface, said tape further comprising an adhesive on said bottom surface.

19. A method of producing a tape comprising: providing a coated optical fiber; and supporting the optical fiber with an elongated ribbon.

20. A method of claim 19, wherein the step of supporting the optical fiber includes a step of attaching the optical fiber along the elongated direction of the elongated ribbon.

21. The method of claim 19, wherein the step of providing a coated optical fiber includes a step of coating an optical fiber with a coating.

22. The tape of claim 2 wherein said optical waveguide is affixed to the elongated ribbon.

23. The tape of claim 2 wherein said ribbon has a hollow region along its length and said optical fiber lies within said hollow region.

AMENDED CLAIMS

[received by the International Bureau on 09 April 1999 (09.04.99); original claims 1 – 23 replaced by amended claims 1 – 22 (3 pages)]

Claims:

1. A tape (40) to be mounted on a structure, said tape comprising:
an elongated flexible ribbon (60); and
an optical waveguide (50) supported by and affixed to the elongated ribbon along the elongated direction of the ribbon.

2. The tape of claim 1, wherein the optical waveguide is an optical fiber.

3. The tape of claim 2, wherein the optical fiber includes a Bragg grating.

4. The tape of claim 2 or 3, wherein the optical fiber includes an outer coating (58).

5. The tape of claim 1, further comprising a second optical waveguide held along a groove in the elongated direction of the ribbon.

6. The tape of claim 4 or 5, wherein the outer coating (28) has a thickness and flexibility chosen to isolate substantially the optical fiber from the structure.

7. The tape of claim 4 or 5, wherein the outer coating (58) has a thickness and flexibility chosen to allow effective transfer of strain from the structure to the optical fiber.

8. The tape of claim 2 to 7, wherein the optical fiber includes a plurality of Bragg gratings.

9. The tape of claim 2 to 8 wherein said ribbon has a top surface and a bottom surface, said tape further comprising a bonding layer (66) on said bottom surface.

10. The tape of claim 2 to 9 further comprising a core (302) around which the ribbon and optical fiber are wound.

11. A tape (100) to be mounted on a workpiece, said tape comprising:

an elongated flexible ribbon (102);

a first optical waveguide (80) supported by and affixed to the elongated ribbon along the elongated direction of the ribbon; and

a second optical waveguide (90) supported by and affixed to the elongated ribbon along the elongated direction of the ribbon.

12. The tape of claim 11, wherein the first optical waveguide is a first optical fiber and the second optical waveguide is a second optical fiber.

13. The tape of claim 12, wherein the first optical fiber includes a Bragg grating.

14. The tape of claim 12 or 13, wherein the second optical fiber includes a Bragg grating.

15. The tape of claim 12 to 14, wherein the first optical fiber include a first coating (88) and the second optical fiber includes a second coating (98).

16. The tape of claim 15, wherein the first coating has a thickness and flexibility chosen to substantially isolate the first optical fiber from strain in the workpiece.

17. The tape of claim 15 or 16, wherein the second coating has a thickness and flexibility chosen to allow effective transfer of strain from the workpiece to the second optical fiber.

18. The tape of claim 12 to 17 wherein said ribbon has a top surface and a bottom surface, said tape further comprising an adhesive on said bottom surface.

19. A method of producing a tape (40) comprising: providing a coated optical fiber (50); and supporting the optical fiber with an elongated ribbon (60).

20. A method of claim 19, wherein the step of supporting the optical fiber includes a step of attaching the optical fiber along the elongated direction of the elongated ribbon.

21. The method of claim 19, wherein the step of providing a coated optical fiber includes a step of coating an optical fiber with a coating (58).

22. The tape of claim 2 to 21 wherein said ribbon has a hollow region (61) along its length and said optical fiber lies within said hollow region.

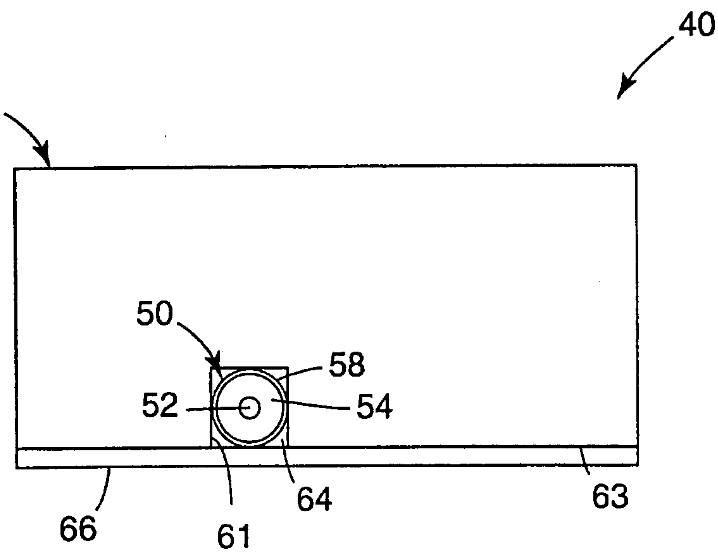


Fig. 1

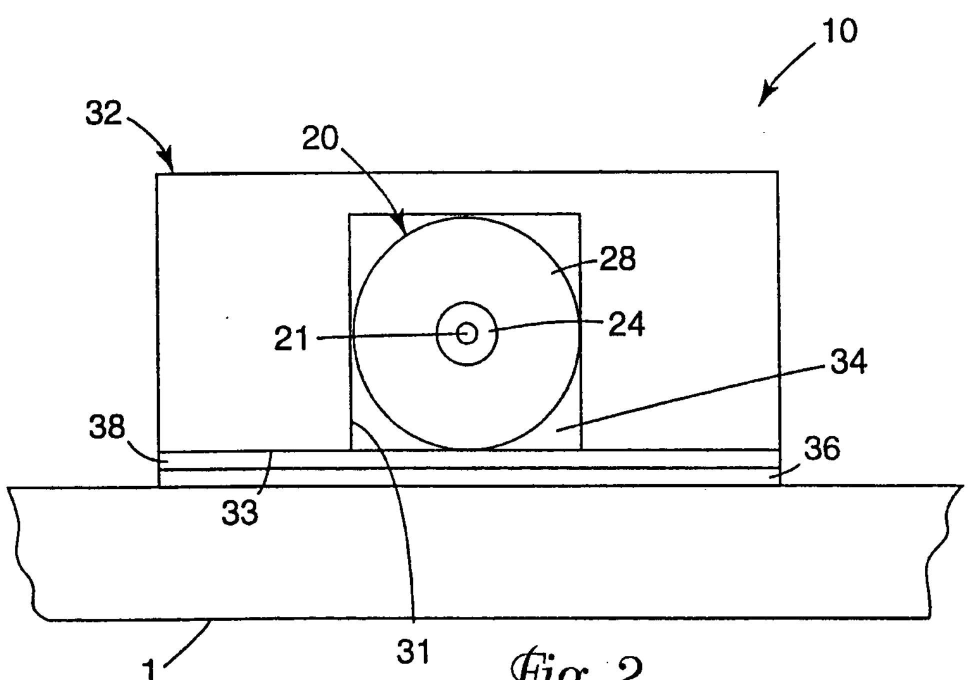


Fig. 2

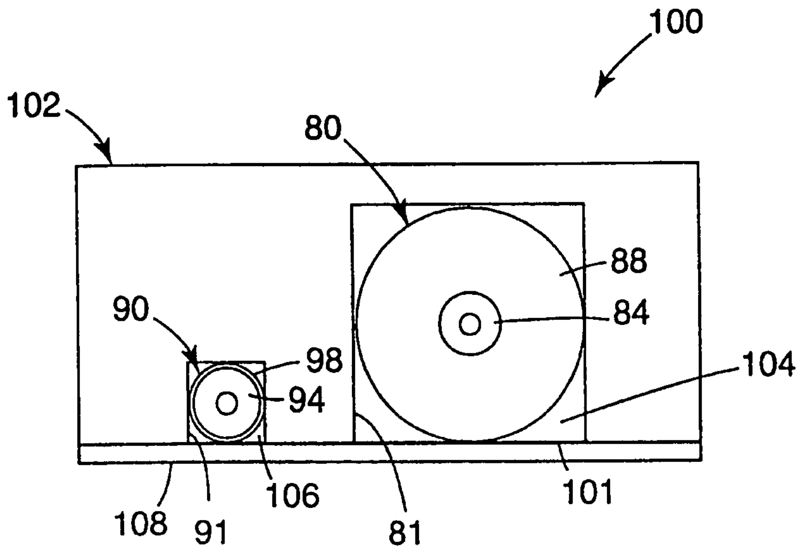


Fig. 3

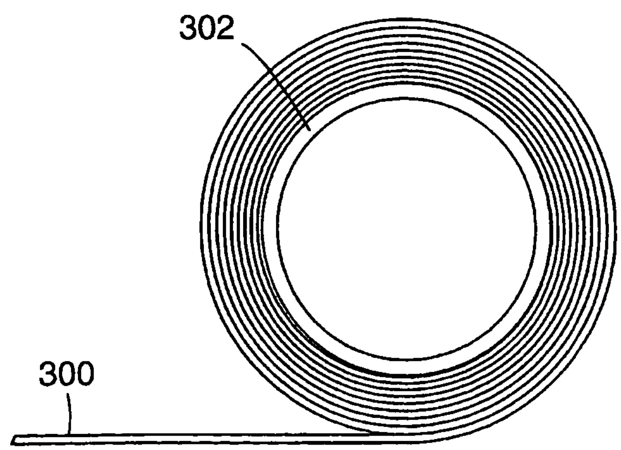


Fig. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/19336

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01L1/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01L G01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 723 857 A (BALL ANDREW ET AL) 3 March 1998 see column 1, line 21 - line 27 see column 1, line 54 - column 2, line 14 see column 2, line 60 - line 67; figure 1 ---	1-3,9, 11-14, 19-22
X	EP 0 384 649 A (SIMMONDS PRECISION PRODUCTS) 29 August 1990 see column 2, line 17 - line 25 see column 2, line 45 - line 53 see column 5, line 1 - line 14 ---	1,2,9, 11,12, 19-22
A	US 4 806 012 A (MELTZ GERALD ET AL) 21 February 1989 see column 2, line 21 - line 31 see claims 1,2; figure 1 --- -/--	1-10,22, 23

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
12 February 1999	19/02/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Klocke, S

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INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/US 98/19336

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	CLAUS R O ET AL: "EMBEDDED OPTICAL FIBER SENSORS FOR MATERIALS EVALUTION" JOURNAL OF NONDESTRUCTIVE EVALUATION, vol. 8, no. 2, 1 June 1989, pages 135-145, XP000162097 see page 135, right-hand column, last paragraph - page 136, left-hand column, paragraph 1 see page 144, right-hand column, paragraph 1 ---	1-10,22, 23
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Information on patent family members

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